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A Comparison of CFAST Predictions to USCG Real-Scale Fire Tests

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ABSTRACT: The zone model CFAST was used to make predictions of single room preflashover fire tests conducted in a steel enclosure. These results were then compared with previously published measurements obtained in fire tests. Tests included diesel pool fires, polyurethane slab fires, and wood crib fires. Half of these tests used natural ventilation (window, 1/4 door, and full door) while the remaining tests used forced ventilation (0.25 m^3/s, 0.38 m^3/s, and 0.61 m^3/s). With the exception of heat release rates, all CFAST inputs were selected without knowledge of the experimental results. Key variables compared include the upper layer temperature, the hot layer interface location, and ceiling temperatures. Overall, predictions made by CFAST were in good agreement with the data. There was a general tendency to over predict both the hot gas layer temperature and the boundary surface temperature which may be due to under prediction of boundary heat losses. Experimental results showed that heat release rates varied with ventilation configurations by as much as a factor of 3. This observation indicates that the wide practice of using free burn heat release rate data in compartment fire predictions can result in over prediction of compartment fire conditions.

KEY WORDS: fire modeling, real-scale testing, verification and validation, pool fires, furniture calorimeter, CFAST.

INTRODUCTION

THERE IS AN ongoing need to expand upon the existing comparisons between fire test data and the model predictions which are widely used in the assessment of fire hazards. These comparisons are valuable in assessing the accuracy of

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the models and their range of applicability. This paper presents a comparison of fire compartment thermal conditions and interface height as predicted by CFAST with experimental results from pre-flashover fire tests conducted in a mockup of a typical shipboard compartment.

The effort to develop computer based models has been paralleled by a continual effort to determine the accuracy of the predictions by comparing the models to laboratory experiments. HARVARD V was used to model eight well-instrumented full-scale room fires by Mitler and Rockett [1]. They reported "good to excellent" agreement for most of the model variables studied. Later, Rockett et al. [2] compared real-scale multi-room fire tests to the HARVARD VI multi-room model [3]. The model gave "favorable" comparisons but several areas for improvement were identified. A limited set of comparisons between multi-room fire tests and the FAST model was made by Jones and Peacock [4]. Levine and Nelson [5] studied a fatal residence fire using real-scale tests and simulations with two fire models (FAST and HARVARD VI). They found the models predicted remote room CO build up and pre-flashover temperature well, but did not predict post-flashover temperatures as well. The models gave "good approximations to significant deviations" on other measurements. Nelson and Deal [6] took data from fire experiments conducted in a small room to determine relative performance of four fire models (CCFM [7], FIRST [8], FPETOOL [9], and FAST). They found all the models simulated experimental conditions "quite satisfactorily." Four models (CCFM, FAST, FIRST, and BRI [10]) were compared to large fires (4 MW to 36 MW) conducted in an aircraft hanger by Duong [11]. He found that all the models were "reasonably accurate" for the 4 MW fire, but for the 36 MW "none of the models did well." Three well-documented experiments were used by Beard [12,13] to evaluate four fire models (ASET [14], FAST, FIRST, and JASMINE [15]). He made both quantitative and qualitative assessment of the models for a number of measurements. Peacock, Jones, and Bukowski [16] compared the CFAST model to a range of real scale experiments. They found the model predictions ranged "from within a few percent to a factor of two to three." Time to peak values and temperatures of layers were most closely matched and gas species concentrations were the most poorly matched. They noted that differences in the model and experiments "can be explained by limitations of the model and of the experiments." Bailey and Tatem [17] have compared a modified version of CFAST with experimental data for post-flashover ship compartment fires, including heat transfer to compartments above. Predictions agreed reasonably well for the fire compartment as well as for the deck and the compartment directly above it. The model over predicted temperatures in compartments and decks not directly above the fire compartment. Dembsey, Pagni, and Williamson [18] have compared a series of one room gas burner fire experiments with both CFAST and FIRST. The compartment hot gas layer temperatures ranged up to 800°C and they found that CFAST tended to overestimate room hot layer temperatures by 150°C to 260°C.

The series of experiments used in this analysis was performed by Peatross et al. [19] in support of the development of the United States Coast Guard's Ship Fire Safety Engineering Methodology (SFSEM) [20]. The experiments were conducted on the test vessel Mayo Lykes which is anchored at Little Sand Island in Mobile Bay, Alabama. This ship serves as a platform for conducting various types of experiments related to safety of both cargo and passenger ships.

Predictions of the test results were made using the experimental description contained in the research report [19]. Using heat release rates deduced from experimental measurements, CFAST was used to predict the upper layer temperature, layer height, and ceiling temperature. These were done by a person not associated with the tests themselves. The modeler did not have access to the experimental results until after the predictions were completed, so the comparisons were blind.

EXPERIMENTAL SETUP AND TEST METHODS

A brief summary of the experimental setup and key measurements is provided below. A more detailed description of the test setup is given in Peatross et al. [19]. The test compartment was approximately 3.4 m wide by 3.3 m deep by 3.05 m high (Figure 1). All bulkheads, with the exception of the port bulkhead, were 12.7 mm steel. The port bulkhead was 15.9 mm steel. There were two door openings in the bulkhead which measured 0.9 m wide by 2 m high. One of these served as the ex-

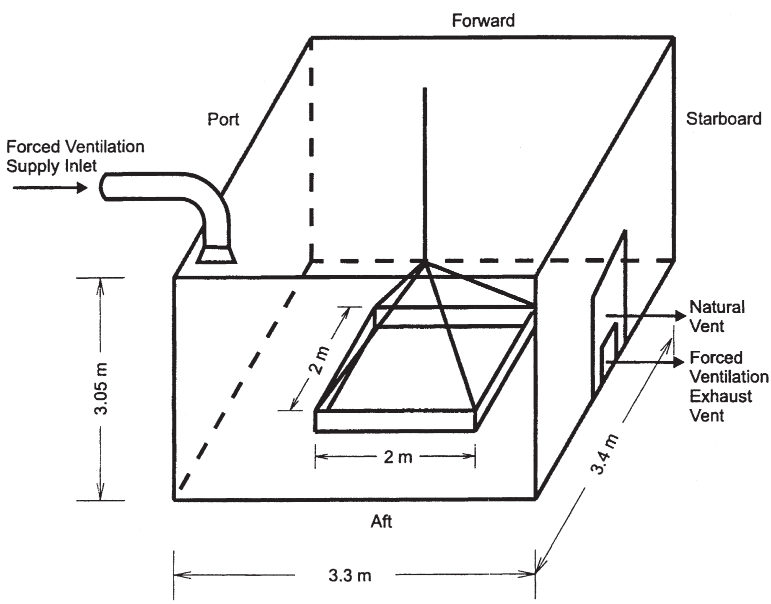

Figure 1. *Schematic of test compartment.*

haust vent and the other served as the room access before and after the tests. The access door was located in the horizontal center of the aft bulkhead (see Figure 1, the portion labeled as "vents" shows the relative position of the vents with respect to the hood) and remained closed during all tests. The second door opening was centered horizontally in the starboard bulkhead and was used to simulate different exhaust vents as explained below.

The tests were divided into 2 series. There were 12 Series 1 tests which used natural ventilation and 12 Series 2 tests which used forced ventilation. Within each series, 3 different vent sizes or ventilation rates were examined in conjunction with 4 fuel configurations. Fuel types used were diesel pan fires, wood cribs (Douglas fir), and (flexible) polyurethane slabs. Two pan diameters, 84 cm and 62 cm, were used for the diesel pan fires. All wood cribs were 1.9 by 1.9 m and consisted of 6 layers of 28 3.8 cm members spaced 3.1 cm apart. The wood was not conditioned prior to use, that is, there was no special treatment to ensure a constant relative water content. Polyurethane slabs measured 1.8 m by 1.8 m by 0.15 m.

A fuel cradle, 2.0 m by 2.0 m, was suspended 0.3 m above the floor in the center of the compartment by a cable extending through the overhead (ceiling). A load cell was attached to the cable so the mass of the fuel could be monitored. The heat release rate was calculated using the mass loss rate and the heat of combustion. Mass loss rates were determined for each point by taking the average rate of weight loss over a two minute interval centered at the point of interest. Heats of combustion used for each fuel were 45 kJ/g for diesel fuel, 13 kJ/g for wood, and 26 kJ/g for flexible polyurethane foam. These values were based on literature values and were confirmed by oxygen consumption calorimetry done separately from these tests [19].

An array of bidirectional probes was used to measure the air velocity in the vent [21]. The number of probes used and their placement differed depending on the ventilation configuration. More specific information is provided below. Three thermocouple trees were used to measure gas temperatures. Two of these trees were located in diagonal corners of the compartment; one in the aft starboard corner and the other in the forward port corner. Each array consisted of 10 thermocouples spaced 30 cm apart. These trees were placed in stagnation regions in the compartment and were necessary for calculating air flow rates. The third thermocouple array was located beside the bidirectional probes in the vent. Thermocouples were also welded to the overhead (ceiling) and the bulkheads at 0.8 m, 1.5 m, and 2.2 m from the floor.

Natural Ventilation Test Series

In the natural ventilation test series, ventilation was provided through a single opening measuring 0.9 m wide by 2.0 m high. It was modified to simulate three different exhaust vents: an open door, a quarter door, and an open window. The quarter door and window vents were simulated by using steel plates to cover the appropriate portion of the doorway. The full door vent was 0.9 m wide by 2.0 m high, the quarter door vent was 0.23 m wide by 2.0 m high, and the window vent was 0.9 m wide by 0.8 m high. Both the full door vent and quarter door vent were flush with the deck while the window vent had a sill of 1.2 m. The maximum compartment ventilation was characterized by the ventilation factor [22], $A\sqrt{h}$, where A is the area of the vent and h is the height of the vent. The ventilation factors for the three Series 1 vent configurations are listed in Table 1.

Natural ventilation tests produced two-layer systems which allowed for the determination of interface heights. The layer interface was taken as the point where the temperature gradient was greatest. Temperatures from thermocouples in the arrays located above this interface point were averaged for the hot layer temperature, and below this point for the cold layer temperature. This method was most suitable for characterizing the thermal environment. Other methods commonly used to define zone model quantities were explored and were found to yield nonphysical results in many cases (see Peatross et al. [19]).

In the full and quarter door vent tests, 13 bidirectional probes were spaced 15 cm apart on the vent centerline. Five probes were spaced 15 cm apart on the centerline of the window vent. Velocities calculated from bidirectional probe and thermocouple measurements were integrated over the height of the vent to determine the exhaust and supply flow rates. The neutral plane was taken as the height at which there was no pressure change across the vent.

Forced Ventilation Test Series

During forced ventilation tests, the opening located in the starboard bulkhead was modified to a 28 cm by 28 cm exhaust vent centered in the bulkhead and flush with the deck. Forced ventilation was supplied to the room via a 30 cm diameter duct which extended from a supply fan. The supply duct discharged into the top of the compartment of the test room at a location 30 cm starboard of the port bulkhead and 24 cm forward of the aft bulkhead. A 42 cm by 42 cm diffuser was attached to the discharge duct to disperse the air. Also, a damper was installed in the duct to control the air supply rate. Table 2 includes the ventilation rates and fuel packages used for Series 2 tests.

Table 1. Series 1 test configurations.

Vent Configuration	$A\sqrt{h}$	62 cm Diameter Pan	82 cm Diameter Pan	Wood Crib	Polyurethane Slab
Full door	2.55	S101	S102	S103	S104
Window	0.64	S105	S107	S106	S108
Quarter door	0.65	S111	S112	S110	S109

Table 2. Series 2 test configurations.

Ventilation Rate	62 cm Diameter Pan	82 cm Diameter Pan	Wood Crib	Polyurethane Slab
0.38 m^3/s	S201	S203	S202	S204
0.61 m^3/s	S207	S208	S206	S205
0.25 m^3/s	S210	S211	S209	S212

The instrumentation for the forced ventilation series was identical to that used in natural ventilation tests with the exception of bidirectional probes. These were located in the center of the supply duct and the exhaust vent. Thermocouples were positioned at these locations as well.

Forced ventilation tests did not produce two-layer systems. The upper layer temperature was calculated by averaging the temperature over the entire compartment height. Interior ceiling temperatures were averaged over the four measurement locations.

MODEL INPUT

The above data were used to create the data files for CFAST. The room and vent geometry was taken directly from the experimental setup. All bounding surfaces were modeled as 12.7 mm thick steel although one of the bulkheads in the test compartment was 15.9 mm thick. An ambient temperature of 20°C was used for all predictions. Other parameters were left at their default values. For example, the radiative fraction is 30%, the gaseous ignition temperature is 100°C over ambient and so on. The technical reference for the model (see Jones et al. [23]) discusses these defaults in more detail.

Although the test compartment was connected to a ventilation corridor system, the simulation used a single compartment connected to the outside. Measurements made in the lower portion of the vent in the natural ventilation tests showed no evidence of recirculation of heated or vitiated gases. Therefore, it is not expected that the corridor played any role in determining the fire environment in the fire compartment. This is typical of well ventilated corridor configurations. During the forced ventilation testing, all air was drawn from a fresh supply so that the flow of smoke into the corridor had no effect on the fire compartment environment.

The fire was located in the center of the room and elevated 0.3 m off the floor to coincide with the cradle used in the experiments. The mass loss rate was used as the primary data for the model. It was defined in the CFAST run as a minimum number of straight line segments, fitted visually to the data by the modeler(s). The prediction and confirmation of the heat release rate (HRR) from the experimental results was the primary means of confirming the correctness of the data set. All simulations were performed without first examining the tests results. Since the fitting of the data was performed with the benefit of only experimental mass loss and heat release rate data, the comparisons shown in this paper are true "blind" experiments.

When the wall surfaces are highly conductive, all components of heat loss are very important, including the enhanced convective heat loss due to the ceiling jet. Increased convective heat transfer to the ceiling reduces the net radiative heat transfer to the ceiling but enhances the radiation to the walls and floor [24]. For that reason the option to calculate the effects of the ceiling jet was used in the simulations.

COMPARISON OF MODELING AND EXPERIMENTAL RESULTS

Any comparison of experimental data with zone model results must be prefaced and qualified. Zone model quantities like hot layer temperature, boundary temperature, interface height, heat release rate, etc. are not measured by individual instruments. Developing experimental zone quantities requires the processing of multiple instrument outputs, sometimes using *ad hoc* methods. As had been noted in the experimental section and discussed in detail by Deal and Beyler [25], the definition of layer temperature and interface location can be defined by a number of these methods. Each method gives a different result and none can be said to have a firm theoretical foundation. Other zone quantities like boundary temperatures can be determined by averaging multiple thermocouple measurements and suffer inaccuracies primarily through practical limitations on the number and placement of boundary thermocouples. Suffice it to say that experimental results from individual instruments are subject to errors, and zone quantities determined from these measurements suffer from practical limitation on the number of instruments, and the *ad hoc* nature of the methods of deducing zone quantities. As such, the accuracy of experimental zone quantities is limited and difficult to quantify. Any assessment of zone model results should be undertaken with these limitations clearly in mind.

Comparisons of the modeling results and experimental results for the natural ventilation tests are shown in Figures 2–5 and in Figures 6–9 for the forced ventilation tests. The measured heat release rates are compared with the fits used in the simulation. The upper layer gas temperatures and ceiling temperatures are compared for all tests and the interface heights are compared for the natural ventilation tests. In forced ventilation tests, the gas analysis results showed that the compartment environment was uniform over the full height of the compartment, while the temperature data showed temperature differences over the height. The effects of ventilation on stratification and layering are further discussed and analyzed in a separate paper [26]. In this comparison, the interface height was taken to be at the

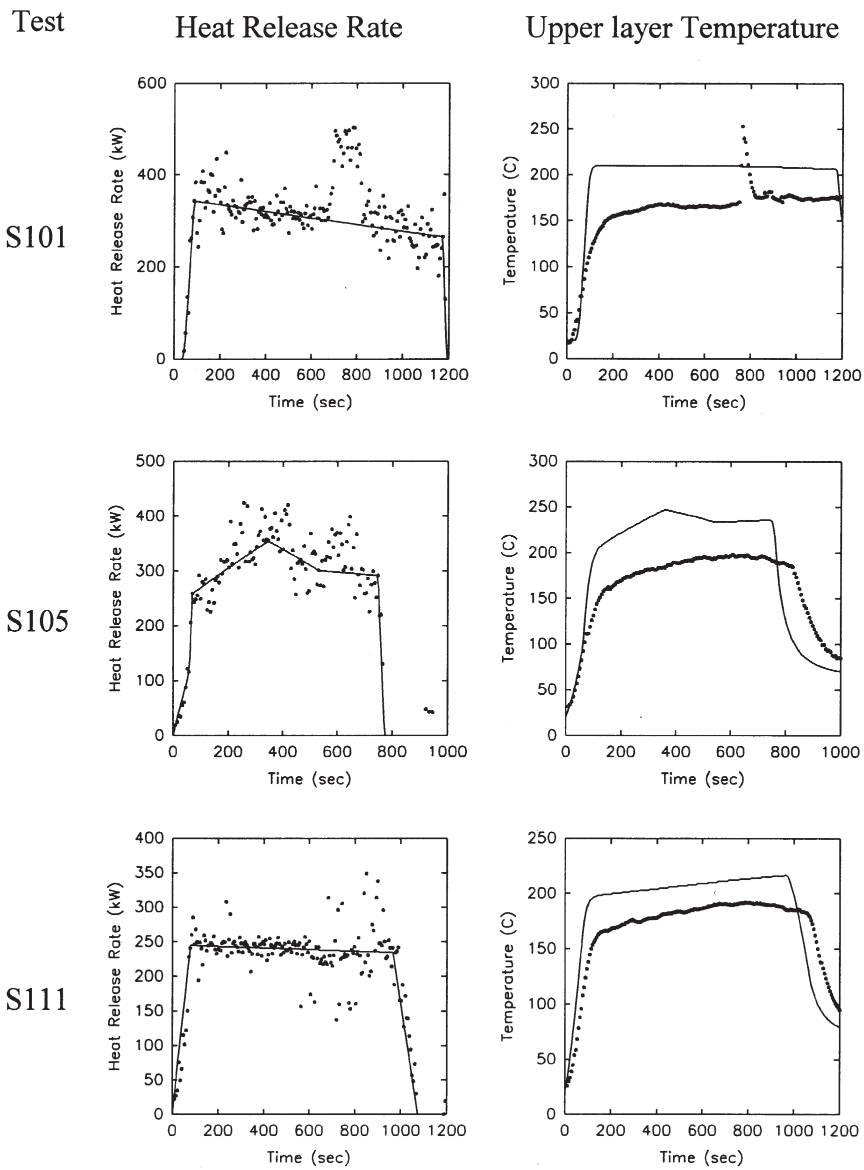

Figure 2. *Natural ventilation 62 cm diameter pan with diesel.*

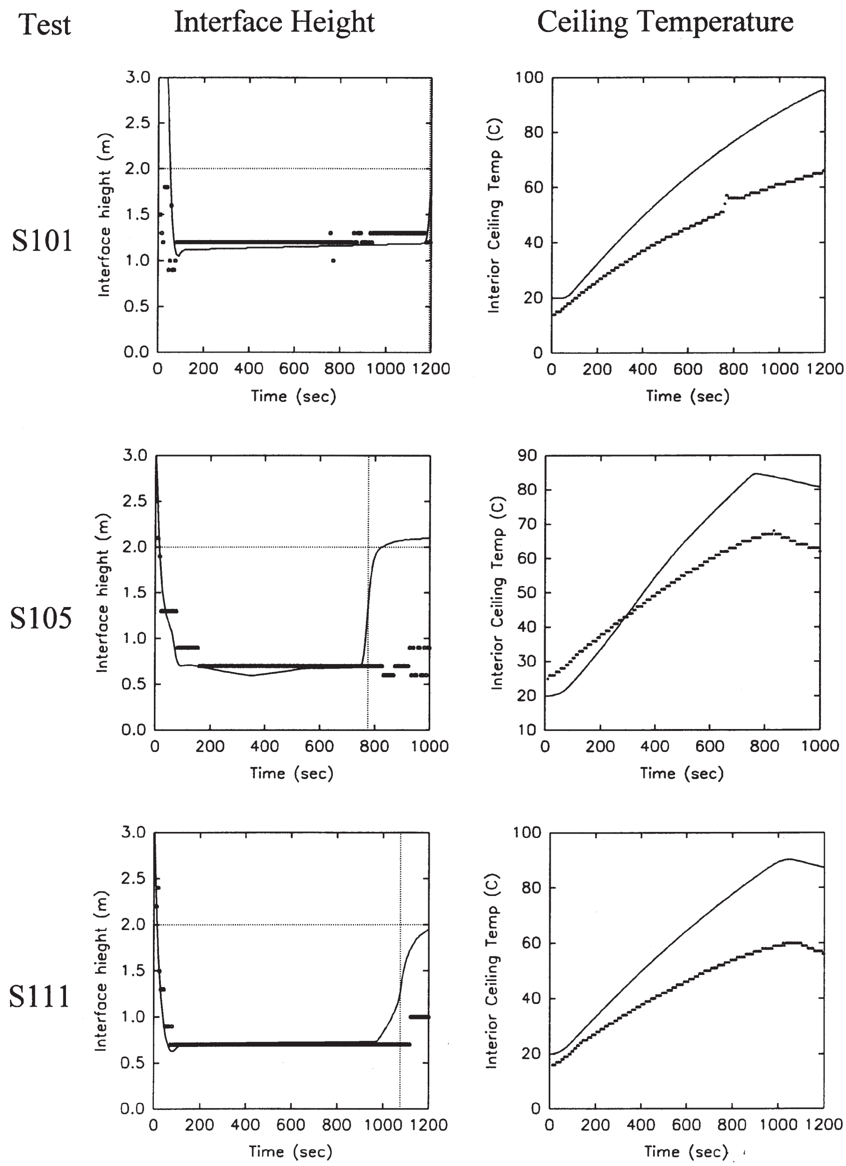

Figure 2 (continued). *Natural ventilation 62 cm diameter pan with diesel.*

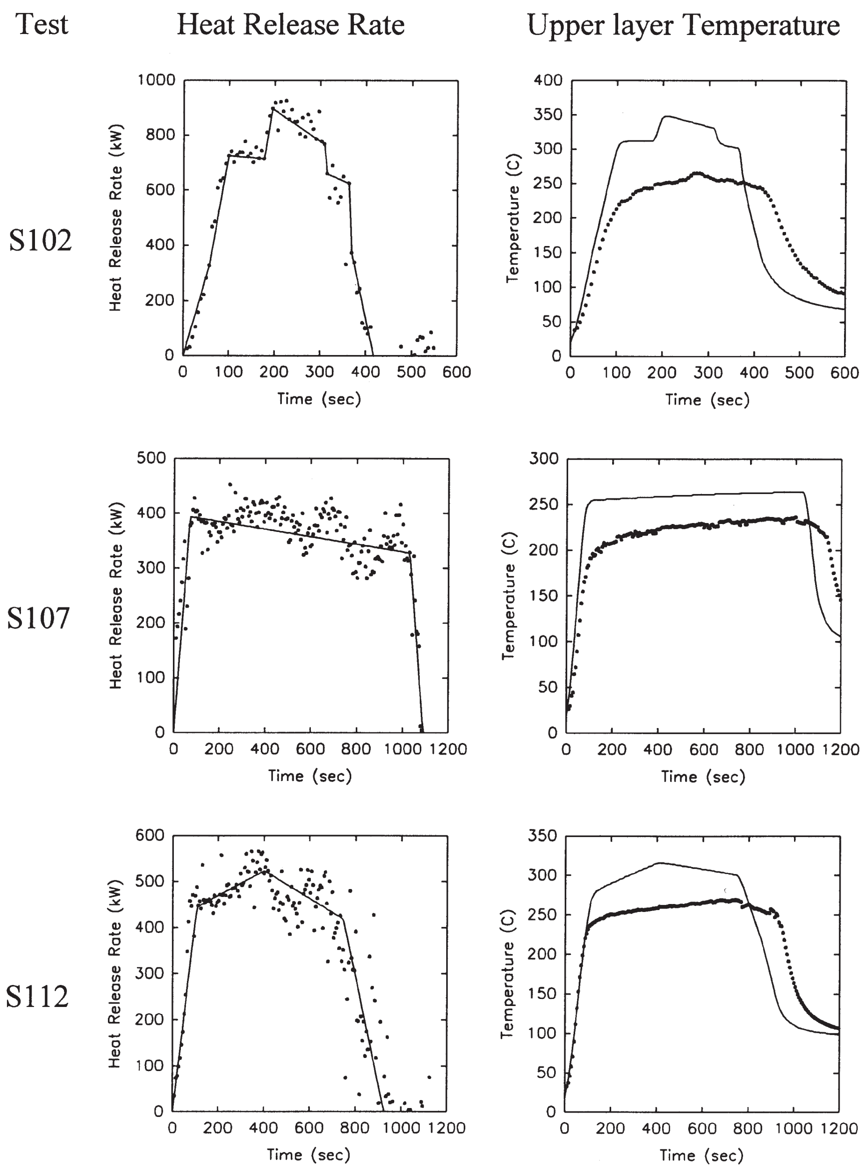

Figure 3. Natural ventilation 82 cm diameter pan with diesel.

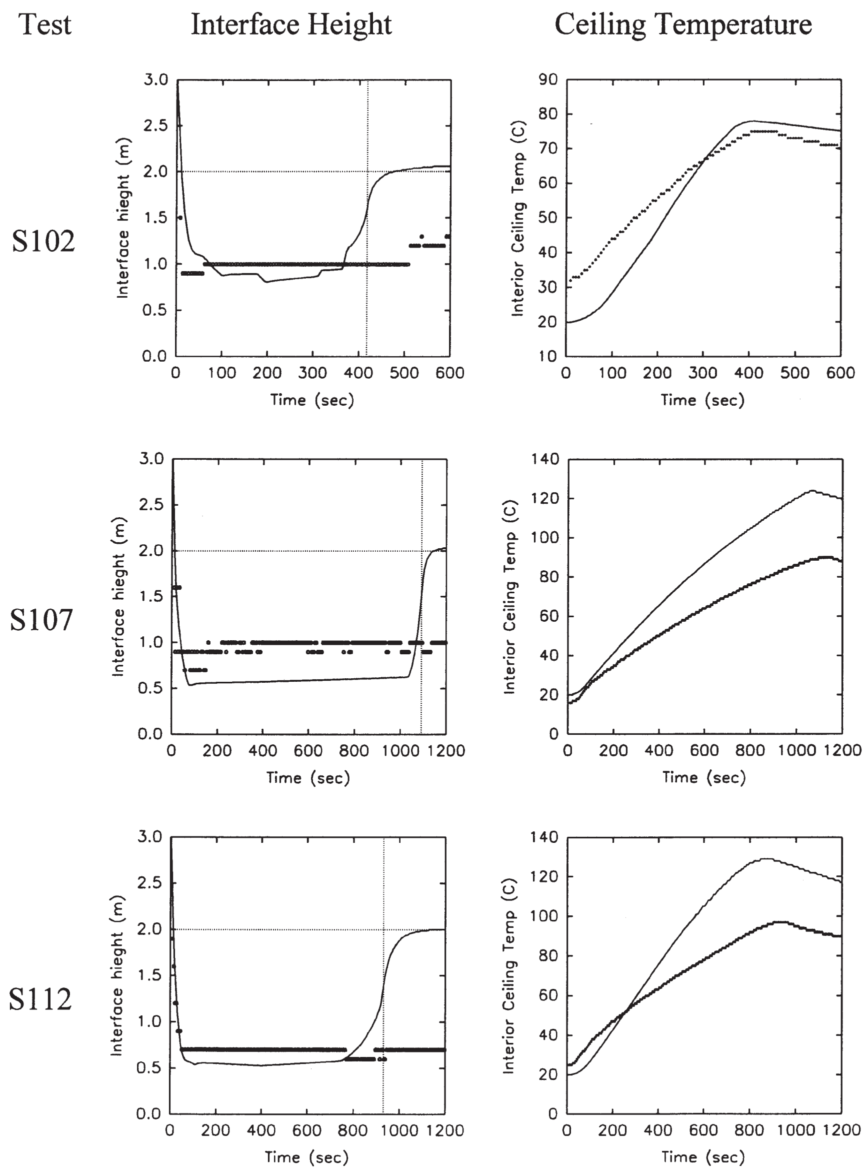

Figure 3 (continued). *Natural ventilation 82 cm diameter pan with diesel.*

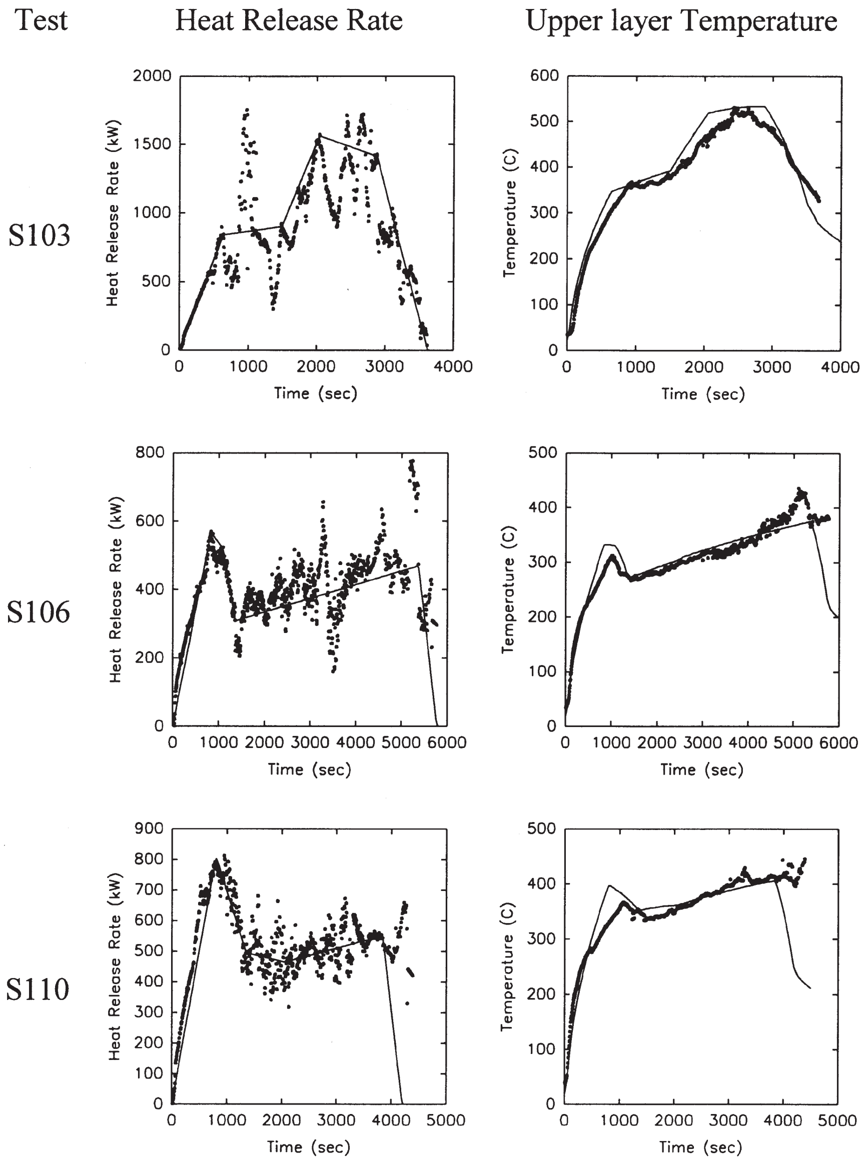

Figure 4. Natural ventilation wood crib.

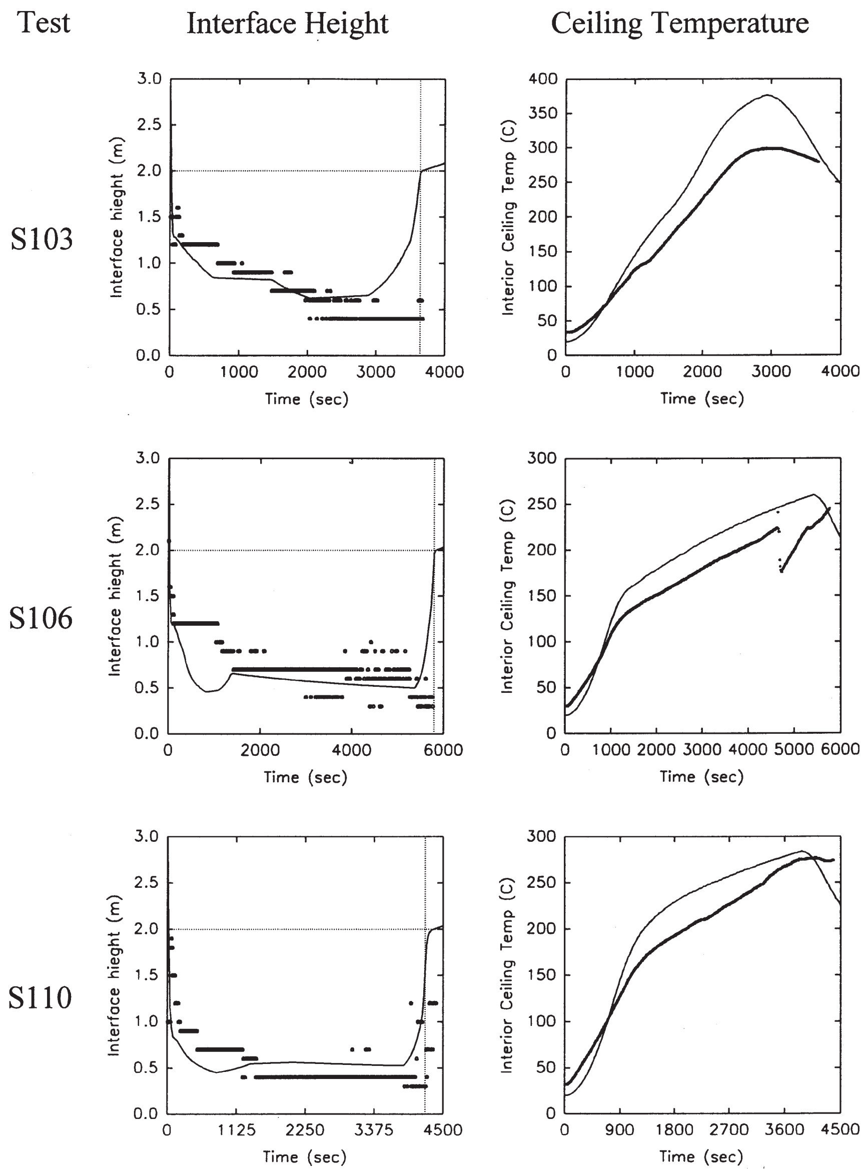

Figure 4 (continued). *Natural ventilation wood crib.*

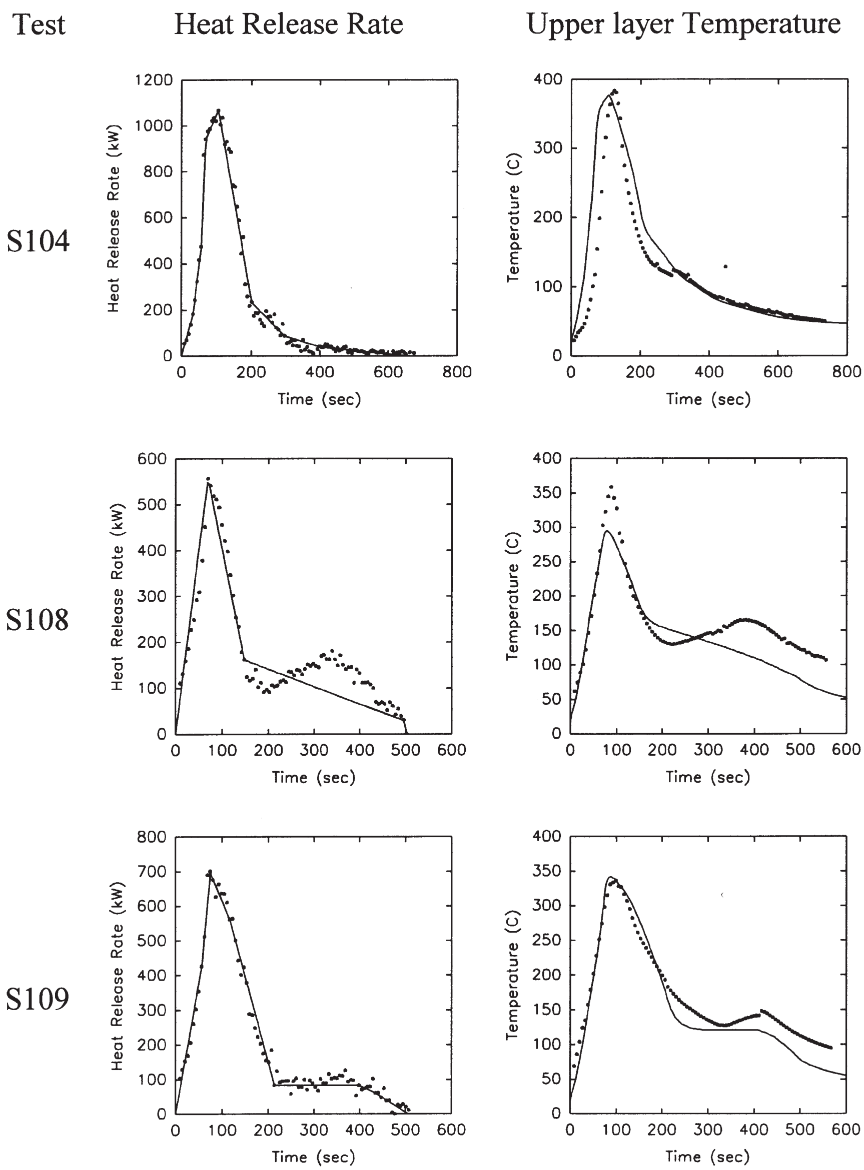

Figure 5. *Natural ventilation polyurethane slab.*

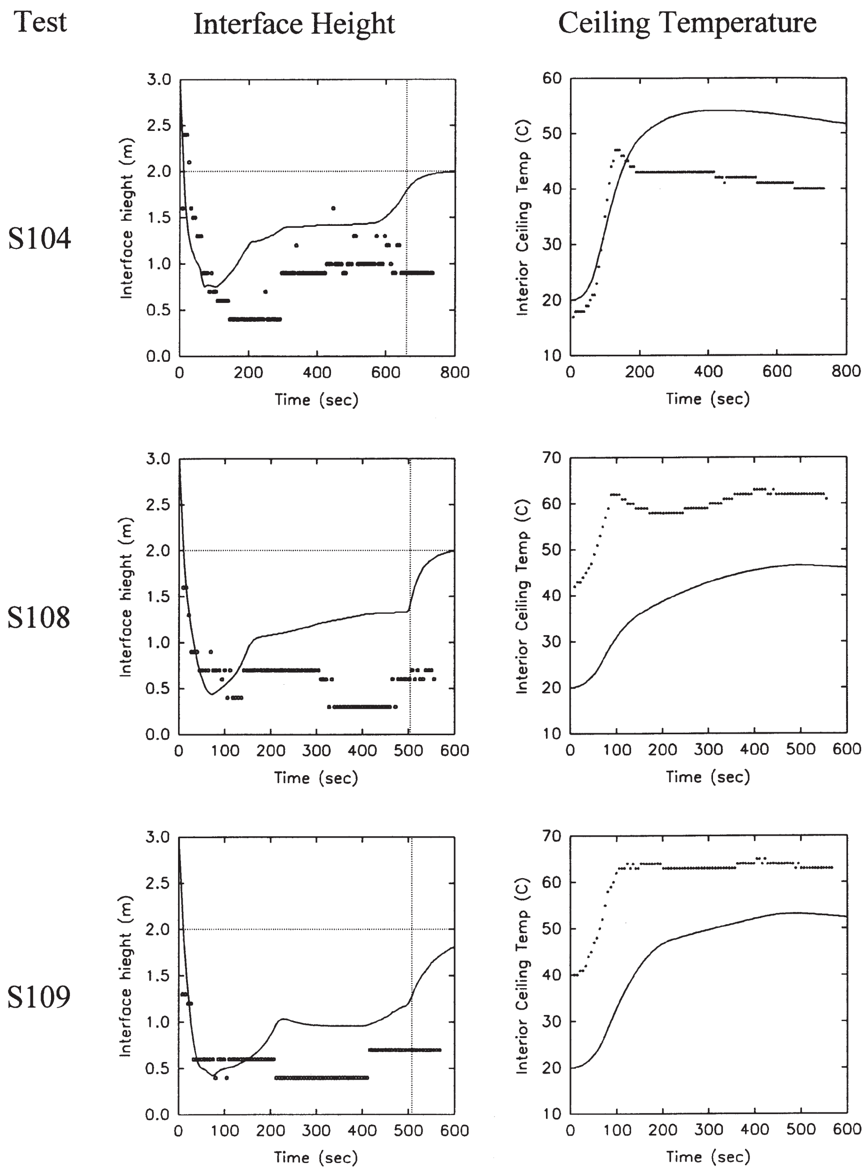

Figure 5 (continued). *Natural ventilation polyurethane slab.*

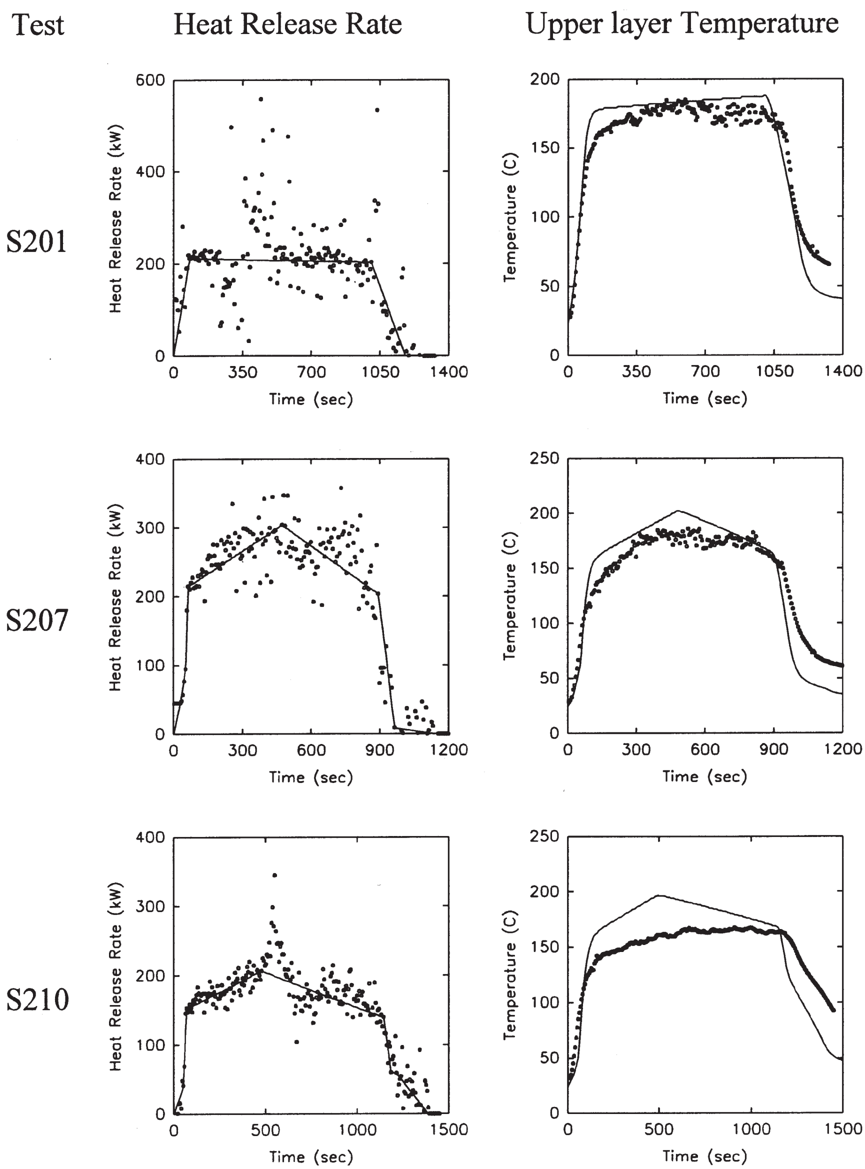

Figure 6. *Forced ventilation 62 cm diameter pan with diesel.*

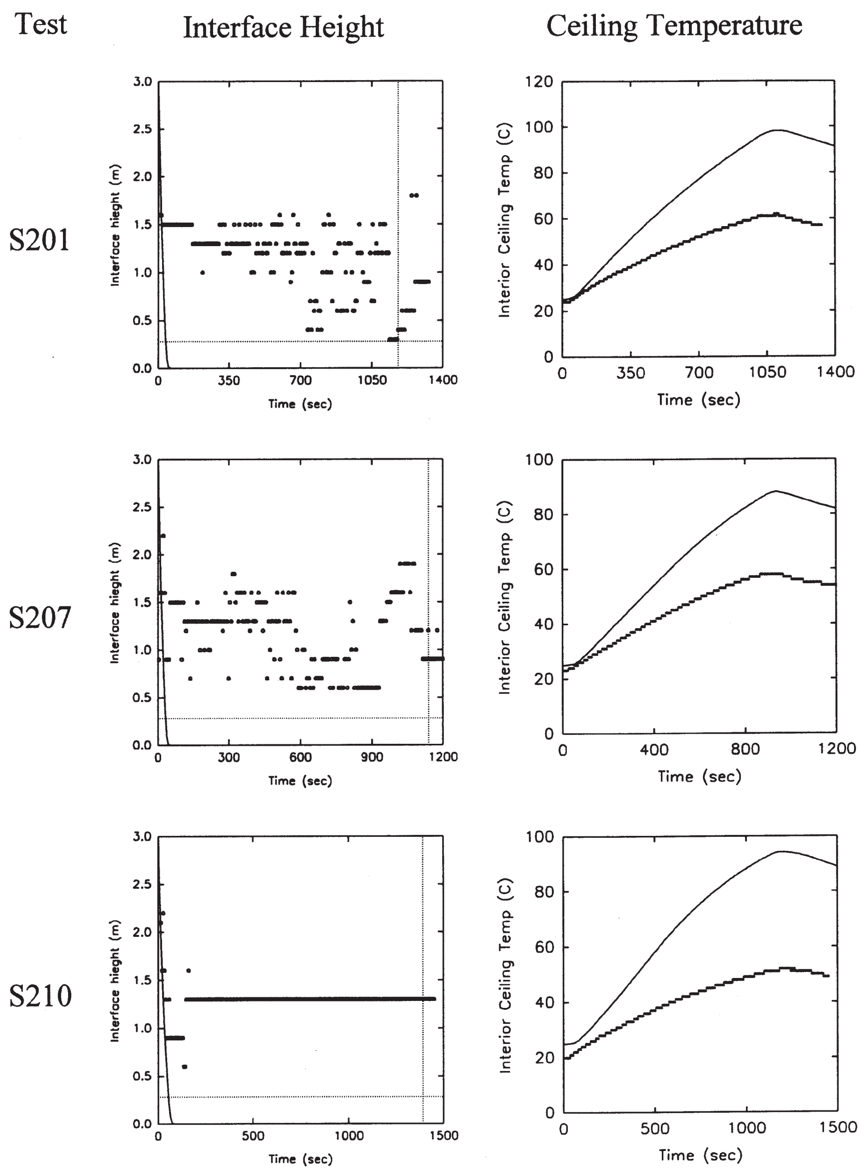

Figure 6 (continued). *Forced ventilation 62 cm diameter pan with diesel.*

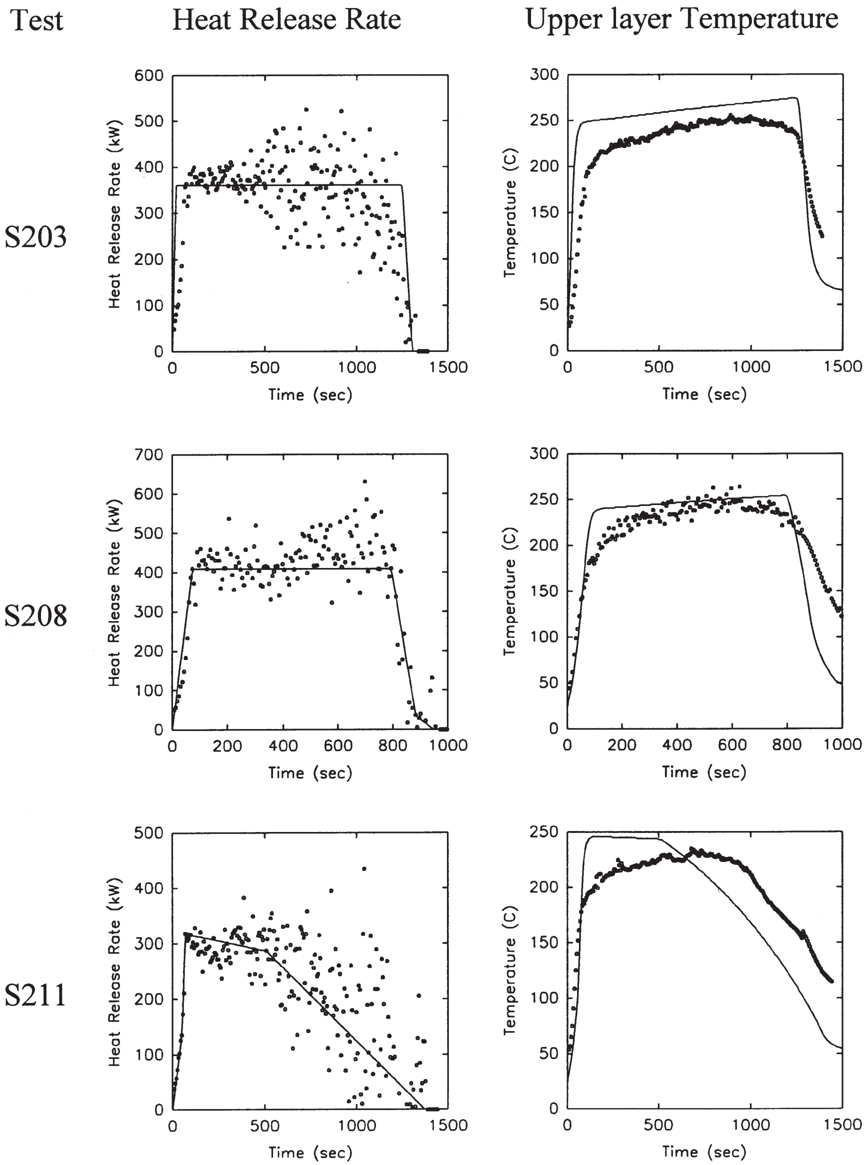

Figure 7. *Forced ventilation 82 cm diameter pan with diesel.*

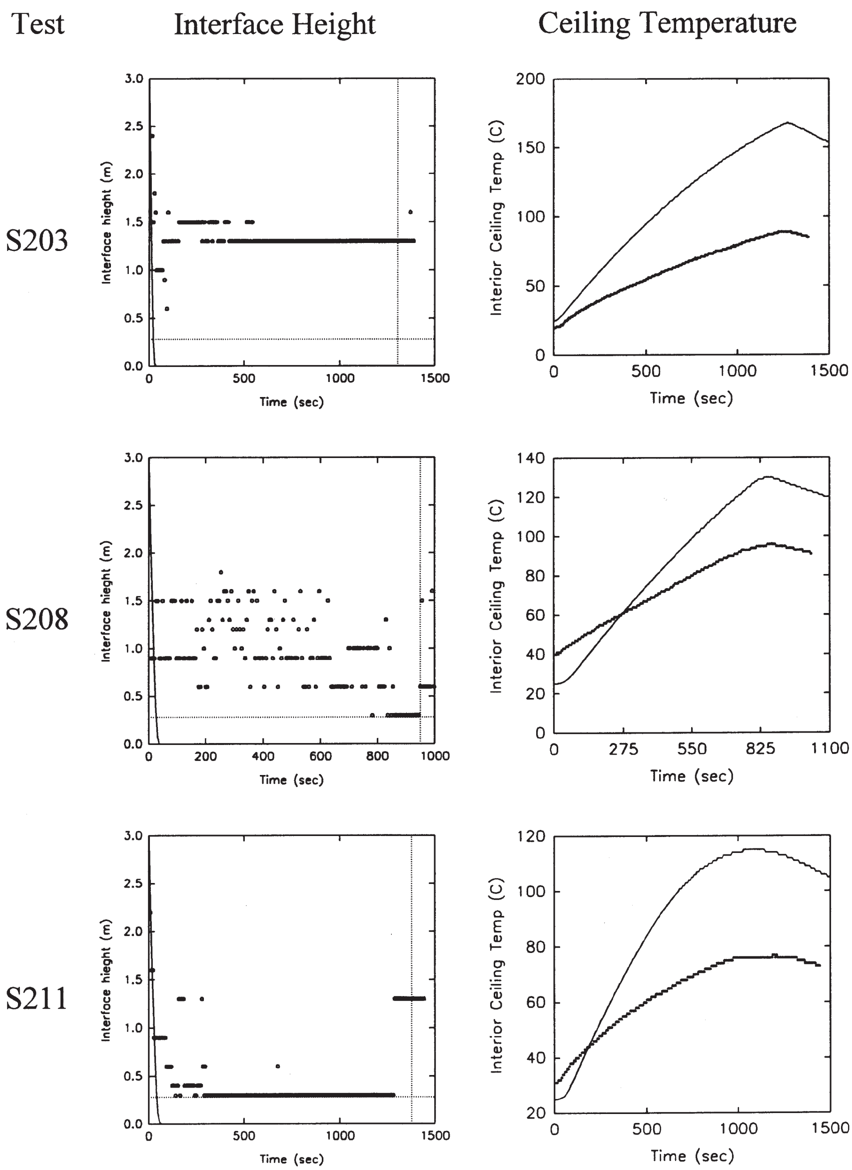

Figure 7 (continued). *Forced ventilation 82 cm diameter pan with diesel.*

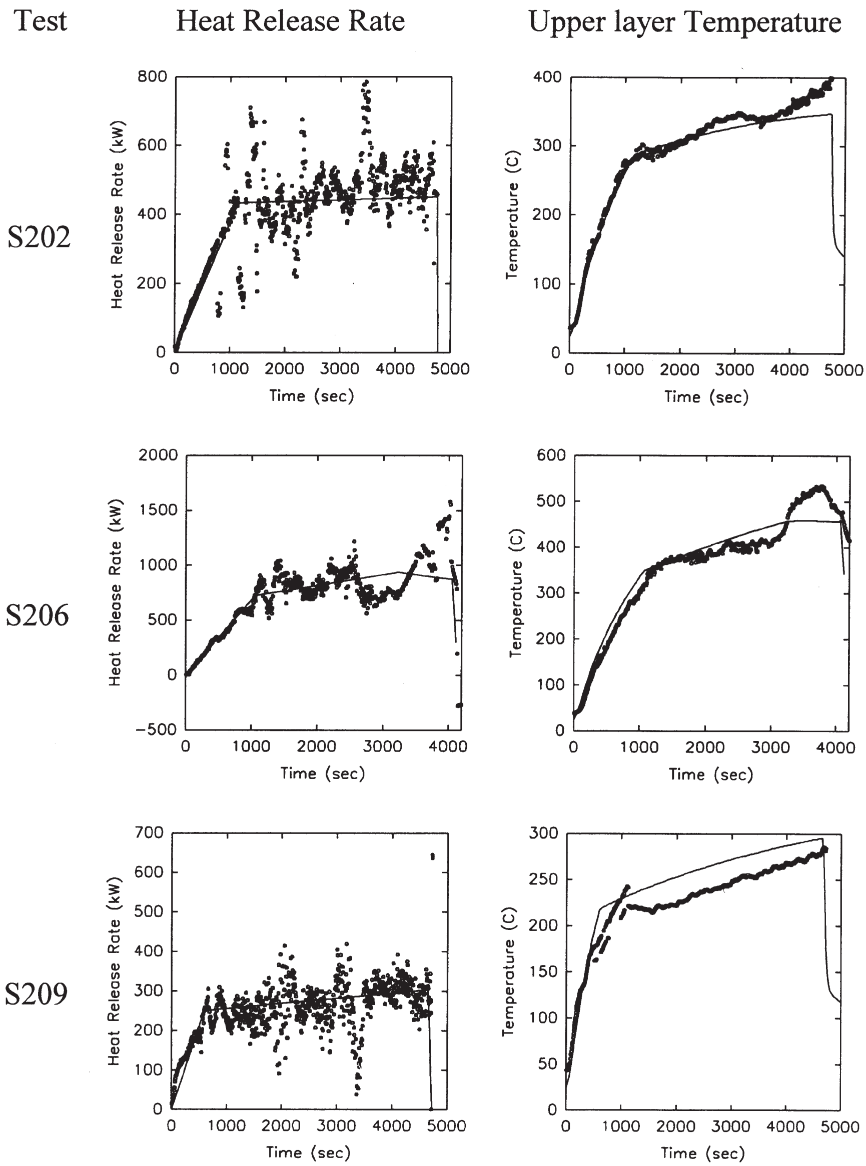

***Figure 8.** Forced ventilation wood crib.*

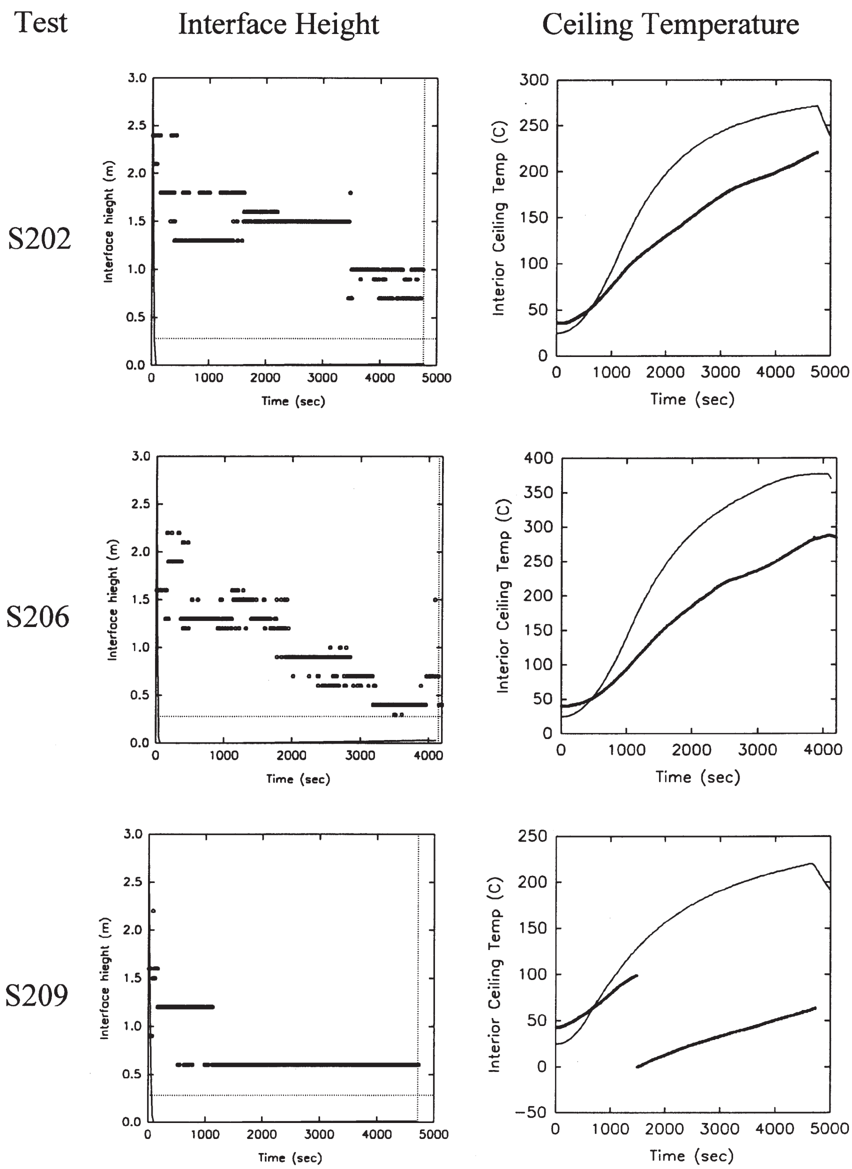

Figure 8 (continued). *Forced ventilation wood crib.*

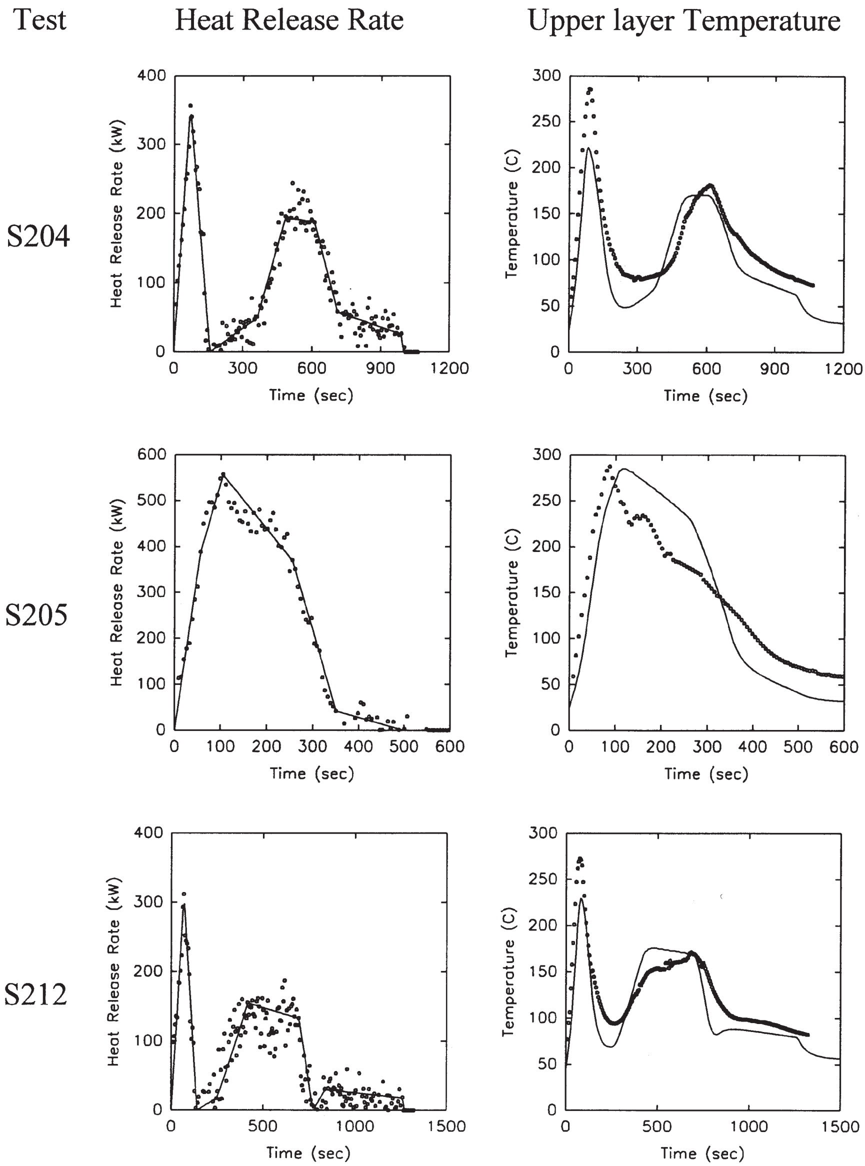

Figure 9. *Forced ventilation polyurethane slab.*

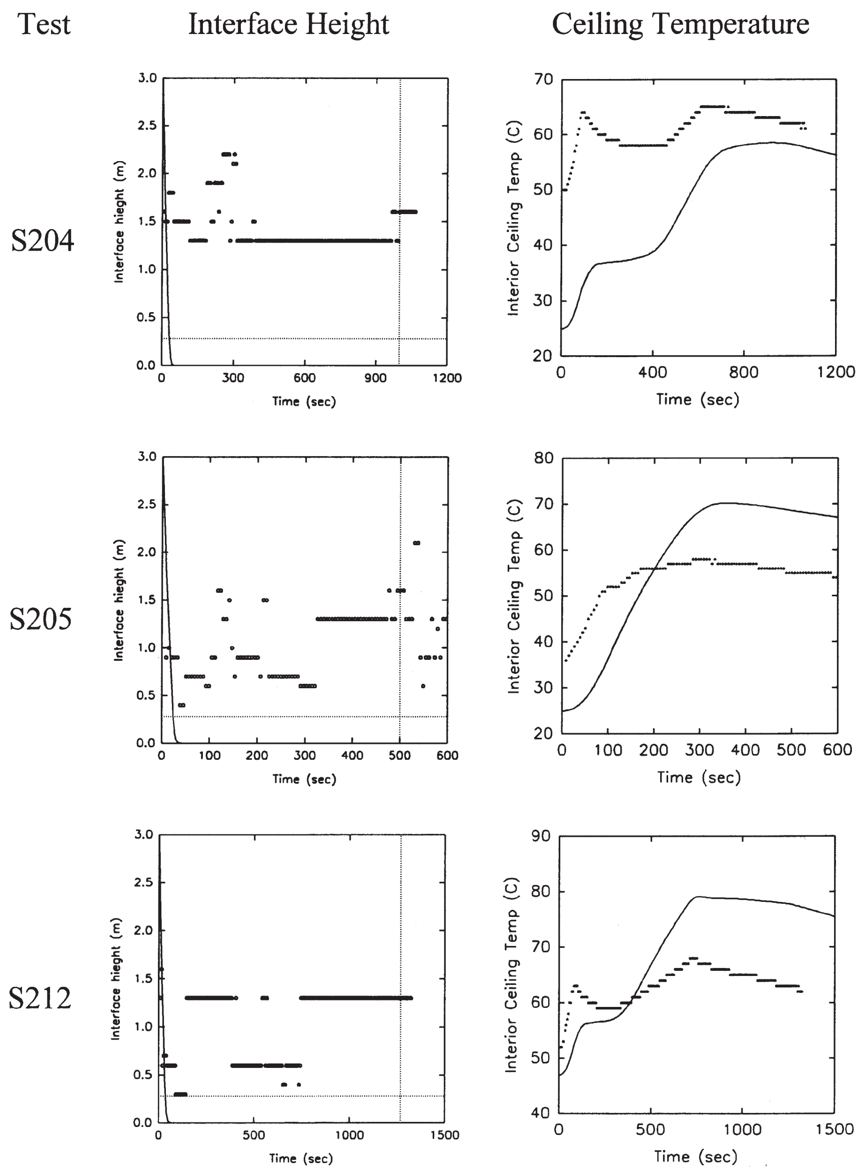

Figure 9 (continued). *Forced ventilation polyurethane slab.*

floor and the upper layer temperature was an average temperature over the full height of the compartment.

In general, the upper layer gas temperatures were predicted to within 50°C with a general trend toward over prediction of the temperatures. The hot gas layer interface locations were very well predicted in the natural ventilation cases except during the burnout phase of the experiments. In this phase, the model generally indicated an increase in the height of the interface which was not reflected in the experimental results. In the forced ventilation tests, the model predicted very rapid movement of the layer to the floor as expected. The temperature of the ceiling as predicted by the model was within 75°C of the experimental results.

While none of the naturally ventilated fires studied in this work were limited by oxygen starvation, there were very definite effects of ventilation on the burning rate of the fuel items. In general, the full door tests had higher heat releases than the 1/4 door or window vent tests with the same fuel item. The ventilation factor for these latter vents was approximately the same and the burning rates in these experiments were similar. The effect of ventilation on burning rate was the greatest for the wood crib and was the least for the smaller diesel pan fire. The effect of ventilation opening on the experimental interface height is generally for the interface to rise as the opening factor increases. This trend is reproduced by CFAST. However, CFAST had some difficulty reproducing the interface location for the polyurethane foam fire during the decay period and for all fires after the fire approached complete consumption of the fuel item. As a practical matter, this is not a serious deficiency.

The agreement between the predicted upper layer gas temperatures and the experimental temperatures was best in the polyurethane and wood crib tests. Some of the error in the other cases can be attributed to difficulties matching noisy data. However, CFAST consistently made predictions for the diesel pan fires which were too high, it being worse on the natural ventilation cases than the forced ventilation cases. The ceiling temperatures were generally over predicted, indicating that heat losses from the compartment were predicted to be less than the actual heat losses. This interpretation is consistent with the general over prediction of the hot gas layer temperatures.

Overall, the upper layer temperature was predicted better in the forced ventilation tests than in the natural ventilation tests. Since the tests were ventilation limited, the heat release rate in the forced ventilation tests was strongly affected by the ventilation rate. Through most of the tests, there was no lower layer present for these cases and plume burning occurred primarily in vitiated air. The ceiling temperature predictions did not follow the trend of the upper layer, indicating that the boundary condition for the far side, unexposed surface, heat loss was too low.

As Peacock et al. [27] pointed out, the HRR curve is the single most important input parameter. The heat release rate is the driving force for the development of the fire environment. In pre-flashover compartment fires, it is widely assumed that heat release rates from open burning calorimeter tests can be used to predict the fire environment. Examining the results of this test series indicates that the heat release rate from the reduced ventilation tests can be as little as one-third of that observed in the largest ventilation condition tests. In terms of the fire conditions in the room of origin and the potential for spread to adjacent rooms, the effect of the compartment size on radiation feedback to the fire is far more significant than any limitation in CFAST.

SUMMARY

An examination of comparisons of "blind" predictions with experimental data support the conclusion that CFAST is generally capable of producing good predictions for gas layer temperature, interface height, and boundary temperature. The important role of heat release rate estimates and expert judgement in the selection of input data as well as the evaluation of the results of model runs has been demonstrated. This comparison also points out the need for better methods of converting test data into model inputs and zone model variables.

The CFAST model usually predicted upper layer temperatures which were higher than the experimental results, though the difference was typically less than 50°C. The high upper layer predictions in part could be caused by the method of calculation of heat losses through the compartment boundaries. This observation is consistent with other published comparisons of test data with CFAST predictions.

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